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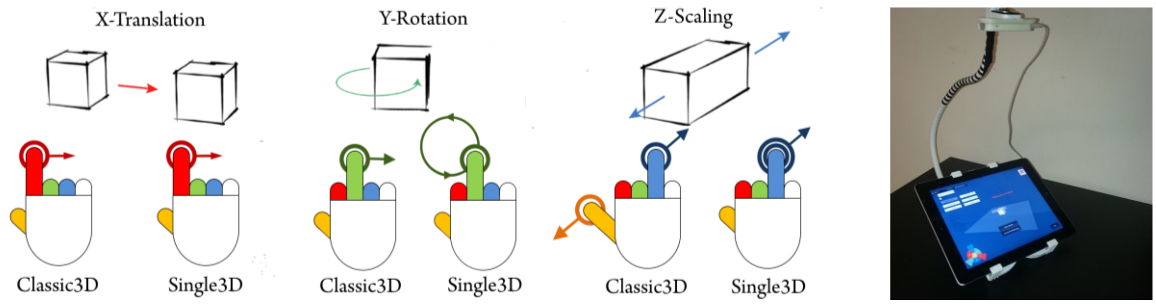

Figure 1: (Left) Axis constraints manipulation gestures for Classic3D and Single3D. (Right) Finger identification prototype.

ABSTRACT

Standard 3D widgets are used for object manipulation in desktop CAD applications but are less suited for use on touchscreens. We propose two 3D constrained manipulation techniques for Tablet PCs. Using finger identification, the dominant hand's index, middle and ring fingers are mapped with the X, Y and Z axes. Users can then trigger different manipulation tasks using specific chording gestures. A user study to assess usability and efficiency permitted to identify the gestures that are the most suitable for each manipulation task. Some design recommendations for an efficient 3D constrained manipulations technique are presented.

Keywords: Touch-based interaction; Finger identification; 3D manipulation; Interaction techniques; Mobiles devices.

Index Terms: H.5.2. Information Interfaces and Presentation: User Interfaces-Interaction styles; I.3.6. Computer Graphics: Methodology and Techniques-Interaction techniques

1 INTRODUCTION

Many CAD applications utilize standard 3D widgets and mice for constrained 3D object manipulations. The recent development of mobile devices has generated new needs for manipulating 3D objects on Tablet PCs. However, the relatively low accuracy of touch inputs and occlusion problems have a negative impact on widgets performance on these devices [2, 13]. In the literature, few touch-based techniques exist for constrained manipulations [1, 2, 7, 10, 12]. While manipulation can be performed seamlessly using these techniques, they still have some limitations [15].

In this paper, we present two new unimanual techniques for 3D manipulation with constraints on Tablet PCs. Based on finger identification, these techniques permit using the index, the middle and the ring fingers to specify constraints on the X, Y and Z axes, respectively. Users can then perform specific chording gestures to trigger the RST (Rotate-Scale-Translate). These techniques embed the selection of constraints, permit determining the operation mode using only one gesture and permit saving the limited screen space. This paper aims to present the design of these techniques and a user study to assess their usability and performance.

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2 RELATED WORK

2.1 Manipulation techniques

Currently, few solutions exist for constrained manipulations on touch surfaces for CAD applications. Schmidt et al. proposed a technique that permits drawing lines to trigger manipulation tasks [12]. Although users have control over 9 degrees of freedom (DoF), memorizing all the gestures is difficult for novice users. tBox [2] and Toucheo [7] are two widget-based manipulation techniques. One limitation is that gestures should be performed near the manipulated object so that the techniques performance may be degraded in a dense cluster. Moreover, some of their gestures are difficult to perform on mobile devices because they require using both hands. Liu et al. have proposed a set of two finger gestures for object manipulation [10]. Objects can be manipulated using the dominant hand (DH) but only 6 DoF can be controlled. Au et al. also designed a set of manipulation gestures using two fingers of the DH [1]. This technique does not require performing gestures upon the selected object but the selection of the constraint is difficult in some camera viewpoints. Recently, Wu et al. [15] proposed a bimanual technique that uses a constraint menu for constraints specification. However, the need of using two hands may restrict its utilization in a mobile scenario.

2.2 Finger identification and chording gestures

To expand the design space of touch-based interactions, some techniques use different fingers to interact with content. Indeed, Colley and Hakkila have shown that mapping fingers to different functions was generally positively perceived by users [3]. For instance, DualKey is a text entry technique based on finger identification [6]. Rather than simply considering individual use of each finger, some researchers have explored the use of finger combinations called chording gestures. Lipinski et al. combined the use of chording gestures with a marking menu to increase the number of menu items [9]. To facilitate chording gestures memorization, Wagner et al. proposed grouping similar gestures using categorical mapping [14]. Goguey et al., used chording gestures to interact with 3D content [5]. Therefore, finger identification and chording gestures open a new path for designing new touch-based interaction techniques. However, to the best of our knowledge, no previous work has used them for 3D manipulation on touch surfaces. Thus our aim is to explore the concept for designing new touch-based manipulation techniques.

3 INTERACTION DESIGN

Two new manipulation techniques are proposed: *Classic3D* and *Single3D*. We have first conducted a needs analysis to describe 3D object manipulation with constraints, and to identify the requirements for a new interaction technique on mobile devices.

3.1 Subtasks for 3D manipulations with constraints

Manipulations with constraints can be broken down into several sub-tasks grouped in three categories:

- Manipulations with a constraint on one axis: Translate, rotate or scale objects along a main axis (X, Y or Z).
- Manipulations with a constraint on one plane: translate or scale objects on a plane defined by two main axes (XY, XZ or YZ).
- Uniform manipulations: permit only to scale objects in all three axes simultaneously (XYZ).

3.2 List of requirements

The list of identified requirements is as follows:

- Users must be able to perform RST independently in all three dimensions; the proposed technique should allow constraints specification on axes and planes.
- To reduce the occlusion problem effects, manipulation should not be affected by the object 3D coordinates; users should be able to trigger manipulation tasks in any position on the screen.
- The operation mode should be changed seamlessly; users can focus on manipulation tasks without being frequently interrupted by additional system control tasks.
- Manipulations should not be limited by camera viewpoints; interaction should work correctly regardless user's perspective.

3.3 Design challenges and rational

To meet the previous requirements, we need to propose enough gestures to control all manipulation tasks. For 2D manipulations, objects can be translated, rotated and scaled using 1-finger drag, 2-fingers rotate and 2-fingers pinch gestures, respectively. However, these gestures cannot be used to control all 3D manipulation DoF. Although we can propose additional gestures for 3D manipulation tasks, the challenge is to find the most appropriate ones that are easy to learn and memorize by users.

The chosen input modality for our techniques is based on finger identification and chording gestures. As discussed above, some interaction techniques have successfully used finger identification to enrich interaction possibilities. Thus, new manipulation gestures can be proposed in the design space provided by the identified fingers. Furthermore, because grouping similar chording gestures into the same category is helpful for gestures memorization [14], we have grouped our gestures according to the manipulation constraints. Thus, we define the concept of "axis-finger" where one finger is associated with one coordinate system axis. The index, middle and ring fingers are associated with constraints on the X, Y and Z axes, respectively. These fingers are chosen because they are adjacent in the hand. Because their order is similar to the order of the X, Y and Z axes, this is expected to help users memorize the finger-axis associations.

To manipulate objects, users can use one or more axis-fingers to specify constraints and then perform specific chording gestures to trigger the desired manipulation task. To explore different chording gestures effectiveness, two techniques are proposed.

3.3.1 Classic3D

This is an extension of the classic 2D manipulation gestures (Figure 1). Indeed, the dragging gesture is used for 3D translation with a constraint on one axis. To translate an object along a main axis, users can drag the corresponding axis-finger in parallel to the desired axis. The same strategy is used for rotation and scaling gestures. For rotation, users use the axis-finger to specify rotation axis, and then drag it in the perpendicular direction to trigger rotation. This corresponds to the metaphor of rotating an object around a pivot. Scaling an object along one axis is performed with a pinch gesture using the thumb and the selected axis-finger. It is unnecessary to perform this gesture in the selected axis direction.

3.3.2 Single3D

Because we think that finger dragging is the most appropriate translation gesture, we have used it also in Single3D. However, rotation and scaling gestures are different. Thus, the proposed rotation gesture for Single3D consists of circling the finger on the screen. This is expected to facilitate its memorization. Users specify constraints using axis-fingers, and then make continuous circular finger movements to control rotations (Figure 1). Rotation direction changes by reversing the circular movement direction.

Some CAD applications allow scaling objects by dragging a scroll bar. However, the dragging gesture is already used for translations. To differentiate between scaling and translation gestures, a double tap with the axis-finger is required to trigger object scaling before dragging the axis-finger along the right (left) direction to increase (decrease) the object size along this axis.

The gestures for manipulations with plane constraints and uniform manipulations for both techniques were designed following the same strategy. In this case, only the axis-fingers change while the gestures remain the same (Table 1).

3.4 Prototype development

There is currently no market-ready technical solution for finger identification. In the literature, various prototypes have been proposed to identify fingers [5, 8, 11]. In our prototype, a low-cost solution similar to Colley and Häkkilä's [3] is used. It is based on using the Leap Motion controller for finger identification.

The Leap Motion controller was installed upside down and fixed on a metal frame attached to an iPad 2 (Figure 1). Finger tracking was performed on a PC and finger identification data was sent to the tablet PC via a wireless network connection. The application was developed on Unity3D with C# and Orion SDK.

Table 1: Gestures proposed for plane and uniform manipulations for both techniques (⓿= thumb, ❶= index, ❷= middle, ❸= ring).

Techniques		Classic3D		Single 3D	
Subtasks	**Axes**	**Fingers**	**Chording gesture**	**Fingers**	**Chording gesture**
Translation with a constraint on one plane	XY	❶+❷	Dragging 2 axis-fingers in parallel to translation axis	❶+❷	Dragging 2 axis-fingers in parallel to the translation axis
	YZ	❷+❸		❷+❸	
	XZ	❶+❸		❶+❸	
Scaling with a constraint on one plane	XY	❶+❷+⓿	Pinch gesture with thumb and 2 axis-fingers	❶+❷	Double tab 2 axis-fingers+ dragging them left/right
	YZ	❷+❸+⓿		❷+❸	
	XZ	❶+❸+⓿		❶+❸	
Uniform scaling	XYZ	❶+❷+❸+⓿	Pinch gesture with thumb and axis-fingers	❶+❷+❸	Double tab axis-fingers+ dragging them left/right

4 User Study

Our user study was conducted to compare the manipulation performance of both techniques and their usability with a focus on three aspects: ease of use, intuitiveness and comfort of the selected chording gestures.

4.1 Participants

Twenty university students (3 women, aged 21 to 39 years) participated in this study. All of them use smartphones frequently in everyday life. Sixteen of them are right handed. Ten of them are novices and 10 are experts in using 3D CAD applications.

4.2 Experimental design, procedure and data

A within-subjects design with one factor (Tech) with two levels: Classic3D Vs Single3D was used. Participants were first taught manipulation gestures and then used them to perform 3 translations, 3 rotations, and 3 scalings with one axis constraint.

Our experiment was divided into 3 phases; teaching phase, training phase and final test. During the teaching phase, subjects were taught successively how to perform the manipulation tasks. For each task, they completed 5 trials in series to learn the gesture. At the beginning of each trial, a 3D white cube was displayed in the screen center. For translation (rotation/ scaling) tasks, a semitransparent target slightly translated (rotated/ scaled) along one axis from the 3D cube was displayed in the scene. Subjects were asked to translate (rotate/ scale) the cube as close as possible to this target. Once the trial was launched, a text message describing the trial goal was displayed on the screen. To explain how to perform the manipulation gesture, both audio and visual instructions were provided. At the beginning of each trial, the first instruction was provided to explain which finger(s) should be pressed on the screen. After this operation was performed correctly, the second instruction was provided to explain how the finger should be moved. Instructions were displayed once, but participants could click a help button to repeat them.

After learning the gestures in Phase 1, subjects were asked during the training phase to accomplish blocks of trials to memorize them. Each block consisted of 9 trials, each eliciting one manipulation task in a random order. Similar to Phase 1, participants had to perform the correct gesture to manipulate the cube as demanded. However, no instructions were provided at the beginning of the trial. If a participant forgot the gesture, he/she was allowed to display instructions. This training process ended when subjects accomplished two blocks of trials in sequence without using the wrong finger/gesture or clicking the help button.

Finally, subjects were asked to accomplish 2 blocks of trials during the final test. Similar to Phase 2, each block consisted of 9 different trials. During this phase, no instructions were provided. The effectiveness of the techniques was evaluated using the completion time. After accomplishing the required tasks for each technique, participants answered a usability questionnaire regarding different criteria, using a Likert scale with 7 levels: 1-very bad to 7 -very good. Moreover, participants were asked to rate the level of comfort of each finger movement. Finally, they were asked to choose the best gesture for each manipulation task.

The presentation order of the two techniques was counter balanced to avoid any learning effect.

5 Results

5.1 Objective measures

A two-way Split-Plot ANOVA shows a significant main effect of technique on the completion time for rotation tasks ($F_{(1,18)}$=5.27, p=0.03) and for scaling tasks ($F_{(1,18)}$=5.05, p=0.03; Figure 2).

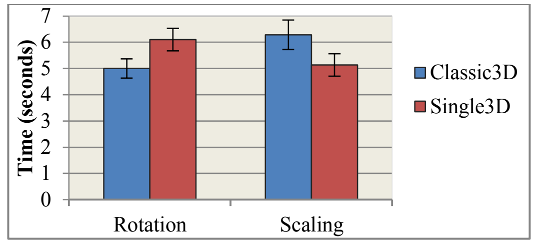

Figure 2: Completion time for both techniques in phase 3.

When comparing fingers performance, a one way repeated measure ANOVA shows a significant main effect of the finger ($F_{(2,38)}$=10.28, p<0.001) on the completion time for translation tasks. The post-hoc tests with Bonferroni correction show that the participants performed the translation using the index significantly faster than the middle (p=0.005) and the ring (p<0.001). No other significant differences were found (Figure 3).

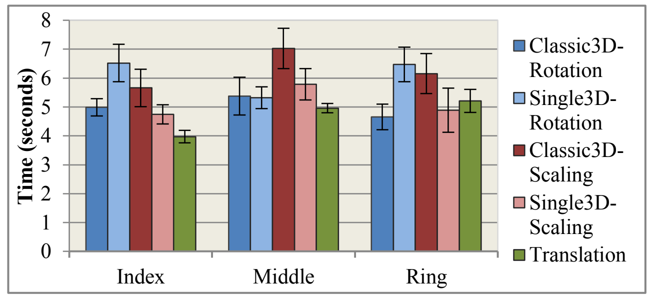

Figure 3: Completion times for both techniques in phase 3.

5.2 Subjective evaluation

Overall, 50% of subjects thought that Single3D is more intuitive, 45% thought that it is the easiest to learn, 65% found it the easiest to use, and 70% of them preferred it over Classic3D.

For rotation gestures, 75% of participants think that circling gestures are more intuitive than dragging gestures. In addition, 60% of them think that they are both the easiest to learn and the easiest to use. Regarding the comfort of use, the Friedman test shows a significant effect of fingers on the comfort for circling gestures (χ^2=26.10, p<0.001). Pairwise comparisons show that subjects found the use of the index significantly more comfortable than the middle (Z=-3.07, p=0.002) and the ring (Z=-3.54, p<0.001), and the middle more comfortable than the ring (Z=3.11, p=0.002). For Classic3D rotation gestures, the Friedman test shows also a significant effect of fingers on the comfort (χ^2=24.78, p<0.001). Pairwise comparisons show that participants judged the use of the index more comfortable than the middle (Z=-3.07, p=0.002) and the ring (Z=-3.54, p<0.001), and the middle more comfortable than the ring (Z=-3.11, p=0.002).

For scaling gestures, 50% of participants found the pinch gestures easier to learn than the double tap+drag gestures. Moreover, 65% of them thought that the pinch gestures are more intuitive. Finally, 65% of them thought that the double tap+drag gestures are easier to use. Regarding the comfort of use, the Friedman test shows a significant main effect of fingers on the comfort for Single3D scaling gestures (χ^2=23.16, p<0.001). Pairwise comparisons show that participants judged the use of the index significantly more comfortable than the ring (Z= -3.16, p= 0.002) and the middle more comfortable than the ring (Z= -3.35, p= 0.001). For the pinch gestures, the Friedman test shows a significant effect of fingers on the comfort (χ^2=30.74, p<0.001). Pairwise comparisons show that participants judged the use of the index more comfortable than the middle (Z=3.46, p=0.001) and the ring (Z=3.74, p<0.001), and the middle more comfortable than the ring (Z=3.10, p=0.002).

Finally, regarding translation gestures, the Friedman test shows a significant main effect of fingers on the comfort ($\chi^2=25.5$, $p<0.001$). Pairwise comparisons show that participants judged the use of the index more comfortable than the middle ($Z=2.52$, $p=0.01$) and the ring ($Z=3.57$, $p<0.001$), and the middle more comfortable than the ring ($Z=3.64$, $p<0.001$).

6 Discussion and conclusion

Based on the observation that widget-based manipulation techniques used in 3D desktop modeling applications are currently not suitable for use on mobile devices, we have presented two constrained 3D manipulation techniques for Tablet PCs based on finger identification as well as a user study to evaluate them.

The usability of the techniques was evaluated across three criteria; the ease of use, the comfort and the intuitiveness of gestures. Most of the participants considered that the circular movements are a more intuitive rotation gesture. However, it requires significantly more time to complete rotation tasks. This can be explained by the fact that our algorithm can recognize the circling motion only after a quarter circle is drawn. Thus, users had to wait until the movement is recognized to start rotation. Second, the Control/Display (CD) ratio for object rotation was set to a high value. Some participants complained that rotations in Single3D were less reactive than Classic3D. Thus, decreasing the CD ratio could improve Single3D rotation performance.

Most of the participants found the pinch scaling gesture to be more intuitive but harder to use than Single3D gesture. Moreover, they needed significantly more time to perform scaling task in Classic3D, more particularly using the ring finger. The double tap required to trigger scaling in Single3D did not impact the task performance in this technique.

The ring finger is found to be less comfortable to use than the index and middle fingers, more particularly for pinch gestures. This is consistent with other studies on fingers comfort for touch based interactions [5] and can be explained by the fact that users are not used to use this finger to interact with touch screens. However, there was no significant difference of performance between this finger and the two others (except for translation). Since the ring is used more naturally in other everyday tasks (eg. typing on a keyboard), an appropriate training period could improve the comfort of using this finger for touch interactions.

These findings suggest that finger identification has its potential value for interaction and can be an acceptable design strategy.

Here are some recommendations to design gestures for a 3D constrained manipulation technique based on finger identification:

- Using the axis-fingers concept is a satisfactory strategy for gestures memorization, more particularly for Single3D.
- Translation gestures based on dragging the axis-finger appears also to satisfy the users and can therefore be reused directly in a 3D manipulation technique.
- Rotation gestures based on circular movements are more intuitive and easier to learn for users. However, some adjustments are still needed to improve their performance.
- The pinch gestures are more intuitive but less comfortable, harder to use and less efficient to perform scaling tasks. A possible design orientation is to give the users the possibility to choose the most appropriate among the two proposed gestures to perform this task, as is the case in many applications.

The proposed techniques satisfy our first, second and third design requirement while the last one is only partially satisfied. In fact, the selected rotation and scaling gestures can be performed independently from the camera viewpoint. On the other hand, the translation dragging gestures need to be performed in the direction parallel to the desired axis which can be difficult to determine when this axis is perpendicular to the screen. This issue is also observed in other state of the art techniques [1, 10, 15] and will require additional investigations to be addressed.

Although the results of our user study permitted us to make some design choices, our assessment was based on a simplified docking task requiring basic manipulations with constraints on one axis at a time. To better evaluate the effectiveness of our techniques, it will be necessary to assess them in a more complex scenario where several basic manipulation tasks should be combined with plane-constraint and uniform manipulations.

Our two techniques were compared with each other to evaluate the proposed chording gestures. However, it will be necessary in the future to compare them with other state of the art constrained manipulation techniques for Tablet PCs. The set of selected gestures will be compared with the recent bimanual manipulation technique that uses a circular menu to control constraints [15]. Indeed, it has shown its superiority over other state of the art techniques (e.g. [1]). This will permit us to improve our technique design and show its efficiency for constrained manipulation.

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